Formulation of Chirp and Impulse Transmitter Requirements for Synthetic Aperture Radar

August Golden
Environmental Research Institute of Michigan (ERIM)
Ann Arbor, MI 48113-4001
Phone: (313) 994-1200 ext.3347
e-mail: golden@erim.org

and

Marc A. Ressler
U.S. Army Research Laboratory
Adelphi, MD 20783-1197
Phone: (301) 394-0839
email: mressler@msc.arl.mil

Abstract

Chirp and impulse waveform choices are examined for use in a postulated airborne ultra-wideband synthetic aperture radar and parameters for transmitters meeting design requirements are developed

Introduction

The next stage of development of the ultra-wideband (UWB) foliage penetration (FOPEN) synthetic aperture radar (SAR) will be to transition it for evaluation in an airborne environment, with an eventual goal of a fielded system suitable for use in an Unmanned Aerial Vehicle (UAV). The work reported here is to estimate the physical and electrical requirements of a transmitter that can produce the necessary power and bandwidth to support such an airborne SAR system. The operational characteristics of the airframe, the assumed target set, and the defined surveillance area can seriously influence the radar parameters. For this study, we estimate the requirements of a SAR system that could be carried on a likely candidate aircraft, the Airborne Reconnaissance Low (AR-L) platform. We have examined linear FM (chirp) and impulse transmitters and identified the necessary waveform requirements. Using existing transmitters that produce similar waveforms as models (such as the UWB P-3/SAR built by ERIM, and the UWB BoomSAR operated by the Army Research Laboratory (ARL)) we estimate the characteristics, weight, volume, and prime power of chirp and impulse transmitters that could meet SAR system requirements.

Impact of Requirements on System Parameters

If the output of a radar system is to be an image that will allow the user to detect and possibly identify targets within the scene, the image must satisfy certain image quality metrics. Of particular interest in the definition of the transmit waveform are the range and azimuth resolution, the noise equivalent reflectivity for additive noise σ_n, and the multiplicative noise ratio (MNR). The resolutions are of interest as they determine the number of independent points into which a target may be resolved, which in turn affects our ability to identify the target. The noise reflectivity, MNR, and scene reflectivity determine the signal-to-background ratio for the image (how "washed out" the image is), which may affect our ability to find a target to identify. The MNR is composed of three major elements: analog-to-digital (A/D) converter quantization and saturation noise, integrated sidelobe ratio (ISLR), and ambiguous energy due to aliasing in both range and Doppler. Allowable system errors for equivalent noise and MNR need to be budgeted among the contributing error sources, and this budget will vary for each system design. We concern ourselves here only with the ambiguity contribution to the MNR, as the ISLR and A/D contributions have less influence on waveform requirements. (These last two contributors are not uncoupled from the transmitter requirements, however.)

For the SAR requirements, we assume that 0.5-m range and azimuth resolution are required to locate and identify tactical targets. We specify the noise equivalent reflectivity at −30 dB, as this is the approximate backscatter coefficient of grass at a 30° depression angle. This should allow good contrast between forested areas (with a reflectivity of approximately −10 dB) and grassy or other low-return areas such as roads and water. Detection of targets within foliage is limited by the forest clutter level, not the noise [1]. Consistent with Lewis et al [1], we set the total MNR at −15 dB, but we set a goal for the range or Doppler ambiguity contributions to at less than −25 dB. Thus, if the A/D contribution is −29 dB, the ISLR contribution can be −15.65 dB. This allows us to use a simple Taylor-weighted ISLR of −20 dB to compensate for degradation due to motion compensation errors. Finally, we assume stripmap SAR operation at a center frequency of 550 MHz. Since target identification is desired, we assume that both vertical and horizontal polarizations are necessary, and that two independent channels receive the return from each transmission of alternating polarization.

The AR-L platform is a DHC Dash 7 airliner, with a maximum cruising speed of 116 m/s, a service ceiling of 6400 m, and a range of 2200 km. If we assume the maximum depression angle for SAR imaging to be 60°, and the minimum depression angle to be 15° (required to maintain good foliage penetration), then the minimum and maximum sensor ranges are 7355 and 24,600 m if the aircraft is at its service ceiling. Within this range interval, the width of the imaged swath, in the slant plane, is assumed to be 1000 m. We assume that this aperture is boresighted at a constant depression angle of 30°. We assume a range of platform velocities near the maximum cruising speed, specifically 100–120 m/s, for this study. The selected altitude and velocity are extreme values, and are thought to stress the system design.

Derived parameters are then as follows. The maximum pulse width is defined by the minimum range as 49 μs. The RF bandwidth necessary to achieve the required range resolution is 360 MHz. The collection angle Ω necessary to achieve the required azimuth resolution is 38.2°, and is provided by a single, broadside-pointing antenna beam. The maximum pulse repetition frequency (PRF) is based in part on the transmitted pulse width, number of polarizations used, swath width required, and the number of receive channels available. The maximum PRF is a function of slant range, and for the maximum range the PRF should be less than 2200 Hz. Determination of the constraint placed on PRF by the range ambiguity requires the definition of the antenna elevation pattern. The horizontal and vertical antenna patterns are based on the P-3/SAR antenna design. We choose the –3 dB horizontal beamwidth (for horizontal transmit polarization) to be equal to the required collection angle at the center frequency. Since range ambiguous energy comes from scatterers at ranges greater than that of the desired swath, their energy relative to that of the desired scatterers depends both on their range and the antenna gain. For the desired range ambiguity, the vertical aperture needs to be twice the horizontal. The horizontal aperture size under the present assumptions is 0.74 m, and the antenna has a maximum gain of 15.7 dB due to the cosine taper in the elevation plane. For the parameters assumed thus far, and for the worst-case lowest RF frequency, the range ambiguity is –24.3 dB at 1100 Hz per polarization (2200 Hz overall).

We next analyze Doppler ambiguity that results when a given PRF is used; the highest transmit frequency is used, as it results in the largest Doppler shift. The Doppler ambiguity derives from the PRF of like-polarized pulses, so for the maximum PRF of 2200 Hz, the effective PRF is 1100 Hz. At the highest platform velocity, Doppler aliasing occurs only if the PRF is lower than 775 Hz. Thus, at the assumed 1100 Hz, no Doppler ambiguity exists. At this point, one might think that all the ambiguity allowance could be used for the range ambiguity, and in some cases this may be true. However, since we have a budget for Doppler aliasing of –25 dB, it may be desirable to use presumming and thus reduce both the data rate out of the receiver, and the amount of data storage required.

Using the parameters developed above, and values typical of the losses observed in the P-3/SAR, we can derive the remaining system parameters and determine the peak transmitter power necessary to achieve the noise equivalent reflectivity requirement, as shown in table 1. For the selected parameters, if the peak power is set to 420 W, the noise reflectivity goal is achieved at all ranges above an 8-km slant range. Reshaping the pattern or changing the depression angle may enable the noise goal to be achieved at all desired ranges. The required peak power increases quickly with a higher depression because the gain of the antenna decreases with increasing range. Reducing the depression angle would reduce the peak power required at the maximum range, but it would also increase the range ambiguity.

Table 1. Chirp SAR parameters

Parameter	Value
Altitude	6370 m
Velocity	110 m/s
Min slant range	7355 m
Max slant range	24610 m
Swath width	1000 m
Azimuth resolution	0.5 m
Range resolution	0.5 m
Center frequency	550 MHz
RF bandwidth	360 MHz
Peak power	420 W
Pulse width	49 μs
PRF (per polarization)	1100 Hz
Antenna gain	15.7 dB
Azimuth beamwidth	38.2°
Aperture size	0.74 × 1.48 m
Depression angle	–30°
Noise eq. reflectivity	–30 dB
MNR	–15 dB
Range ambiguity	–24.3 dB
Doppler ambiguity	–27 dB
A/D noise	–29 dB
ISLR (allowed)	–16.1 dB
Noise figure plus losses	12 dB

If an impulse is transmitted, versus a chirp of some tens of microseconds, the peak power must increase to achieve the required average power. The PRF cannot increase or the range ambiguity suppression will not be achieved. If a 1-ns pulse is assumed, all energy outside

the bandwidth necessary for range resolution is not used, so an additional efficiency must be factored in.

Physical Characteristics of Transmitters

The radar waveform requirements are similar to those of the UWB P-3/SAR. This is not unexpected, as the platform altitude and resultant range are similar to those of the P-3. One approach to estimating the chirp transmitter physical characteristics is to derive them from those of the P-3 transmitter, remembering that it was not optimized with respect to weight or volume and covered a larger frequency range. The P-3 driver amplifier produces two 250-W signals over the 200 to 900 MHz frequency range from a single 0-dBm input signal. These two signals, when combined and fed to the antenna through a duplexer and RF path with a total loss of 3 dB, would be adequate to meet the system requirements. The duplexer can probably be absorbed into the combiner volume and we can absorb the weight and volume of the P-3 exciter in the driver amplifier, but we have not assumed any other reduction in weight or volume of the driver amplifier resulting from a design effort with such a reduction as a goal. The P-3 power supply is scaled linearly in weight and size to produce the power required for the driver amplifier. Column C-1 of Table 2 shows this approach. The P-3 amplifier is a Class AB amplifier with a 200 to 900 MHz bandwidth. The efficiency should improve with a Class B or C design and with a narrower bandwidth. The transmitter harmonics are expected to increase with a Class C design, but the narrower bandwidth will mitigate their effects.

Another approach to estimating the transmitter characteristics is to conceptualize a transmitter from existing commercial units with the required RF bandwidth. The Mini-Circuits LZY series High Power amplifiers provide 50 W cw from a 7,160 cm^3 package, which weighs 4 kg and consumes 190 W of prime power at 26 V. This amplifier family spans the range of frequencies of interest, so a suitable amplifier covering a 360-MHz bandwidth, centered at 550 MHz, could be constructed with 10 LZY series amplifiers to provide the required 420 W of peak power (including the losses of a combiner). These are class A amplifiers, and the normal prime power for 10 units would be 1900 W. However, if the amplifier components can be redesigned to operate Class B, then the existing LZY efficiency and the 11-percent duty cycle result in only 350 W of average prime power at 26 V. If the 400-Hz power supply has an efficiency of 83 percent, 420 W of aircraft power is needed. This choice is column C-2 of Table 2.

Ideally, a chirp transmitter could be designed with the given waveform requirements in mind and using the latest technology. Such an effort could address the benefits of using SiC or field-effect transistor (FET) devices, for example. Representative of what might be achievable by such a design effort, column C-3 in Table 2 was derived by scaling of the predicted characteristics of a chirp transmitter generated by a major manufacturer with significant expertise in transmitter design. The transmitter used for this scaling was designed to operate over at least 220 to 580 Mhz and produce 300 W of peak power; it also includes the waveform generator and exciter.

Table 2. Transmitter estimated values (C=chirp, I=impulse)

Parameter	C-1	C-2	C-3	I-1	I-2
Peak power (kW)	0.42	0.42	0.450	60,000	20,000
Avg. power (W)	45.3	45.3	45	90	30
PRF (kHz)	2.2	2.2	1–4	2.2	2.2
Duty cycle (%)	11	11	10	0.00044	0.00062
Pulse width (μs)	49	49	20–80	0.002	0.0028
Efficiency (%)	10	11	10	11	11
Prime pwr (kW)	0.45	0.42	0.45	0.80	0.26
Vol. ($1000 cm^3$)	161	89	90	192	64
Weight (kg)	78	52	27	141	47.2

The commercially available impulse transmitters used on the BoomSAR consume approximately 8.4 W of prime power at 28 V to produce a 1.5-MW peak output. Power Spectra is developing a higher power transmitter under contract to ARL. This transmitter consists of a power supply/control module, and one or two source modules. Each source module has six outputs, each derived from a Bulk Avalanche Semiconductor Switch (BASS) that discharges a charged transmission line. These outputs can be combined to drive a single antenna, or each output can be coupled to an individual antenna. Each source module can produce a total of 20 MW peak power and 15 W average power. Using the efficiency of the commercially available unit, we estimate that 112 W of prime power would be required for a 20-MW unit consisting of one power module and one source module. Experimental power supplies matched to switch requirements have been constructed with 25-percent efficiencies, which would halve this power consumption. The source modules would be mounted near the antennas. The current output pulse into a resistive load is a fast rise, slow fall, dual exponential with approximately 200-ps rise and 2-ns fall times. Into a 50-Ω load, the output power is 20 dB less at 2.4 GHz than it is at 600 MHz. These units have only been operated up to a 1-kHz PRF. PRFs higher than this are possible at reduced switch lifetime, but with a separate source module, or modules, for each transmit

polarization, operation at 2.2 kHz should be possible. The output pulse drives the antenna, resulting in a radiated field with a time variation given approximately by the derivative of the driving impulse (i.e.; a "doublet") with energy covering the 50-MHz to >1-GHz frequency range. If a third of the radiated energy is in the desired 360-MHz band, it would take three power modules and six source modules to provide the desired average power (column I-1). The weight and size of any power combiners must be added to the budget; 10 kg and 5000 cm^3 per source module are assumed here for driving a single antenna. There are currently no T/R switches that handle the transmitter output directly, and so a separate receive antenna would also be needed. In deriving these estimates, we assume that the combiner loss is negligible, as no duplexer function is required, and that only 11.2 W is required into the antenna, similar to that for the chirp waveform after considering the 3 dB of RF path loss from the transmitter to the antenna.

To better match the transmitter spectrum to the 360-MHz bandwidth specified above, we could modify the impulse source to generate a monocycle waveform, rather than the current fast-rise, slow-fall pulse. Using a folded-charge line and the same switch element, monocycle transmitters have been constructed with 300-MHz-wide bandwidth centered at 300 MHz. They produce 20-MW pulses that are 3.5 ns long at the 1-kHz rate. A modification of this monocycle design is predicted to meet the postulated UWB SAR requirements, using one power module, two transmitting units, and two power combiners. This transmitter would generate 2.8-ns pulses (to achieve roughly a 360-MHz bandwidth) at the 1100-Hz rate for each polarization (column I-2). The system center frequency should also be reduced from 550 to 360 MHz to accommodate the monocycle waveform, and the antenna aperture would have to increase to retain the assumed gain at this lower frequency.

Source Comparison and Summary

A casual glance at table 2 would suggest that the C-3 and I-2 approaches are quite similar in their physical characteristics. However, a closer look is required. For example, the volume required for the receive antenna in the impulse system has not been considered. Also, we have not addressed the method of target discrimination, and the possible requirement to see a specular return from targets of interest for such discrimination. Such factors may lead to the need to consider multiple transmit or receive beams. Therefore, comparison of these two approaches for the generation of SAR signals requires one to conduct a more detailed design effort and review that includes not only the unique characteristics of these sources, but also addresses how the received signals are processed, before forming any conclusions. We here discuss only two of the many areas that warrant such further detailed comparison: The UWB SAR would have to operate in an electronic jamming environment, and its concept of operations would have to address self-jamming of Army communications. In this, the chirp design is more flexible. The transmitter can be designed not to radiate in specific, narrow frequency bands. This was done with the P-3 to prevent interference with various aircraft emergency signals. Also, if longer range performance is required, the chirp duration can be extended without difficulty at the expense of short range coverage, provided the aircraft can provide the average power and provided the Doppler ambiguity can be kept low enough. The emissions from the current impulse system are defined by the hardware (e.g., size of transmission line and locations of switches) and do not offer such flexibility. However, it may be possible to design in more flexibility in future impulse systems.

These UWB systems must operate in the presence of severe radio frequency interference (RFI) caused by commercial broadcast FM and TV stations. Because of the short time window associated with receipt of the impulse data, one can model the RFI signals differently from what must be assumed during the longer chirp data window. The time window required for reception of data in the chirp case must include not only the two-way swath time, but also the length of the chirp. RFI sources, such as commercial FM signals, are more stationary during a shorter time interval. This difference in the nature of the RFI corrupting the desired data may enable the more successful removal of RFI, but may put a larger burden on the A/D converter used in an impulse implementation.

Reference

1. T. B. Lewis, M. A. Biancalana, A. Golden, J. D. Gorman, et al., "Concealed Target Detection Technical Report," ERIM Technical Report 232700-57-F, for the Avionics Directorate, Wright-Patterson AFB, OH, July 1994.

INTERNET DOCUMENT INFORMATION FORM

A . Report Title: Formulation of Chirp and Impulse Transmitter Requirements for Synthetic Aperture Radar

B. DATE Report Downloaded From the Internet 1/5/99

C. Report's Point of Contact: (Name, Organization, Address, Office Symbol, & Ph #): U.S Army Research Laboratory
Marc A. Ressler (301) 394-0839
Adelphi, MD 20783-1197

D. Currently Applicable Classification Level: Unclassified

E. Distribution Statement A: Approved for Public Release

F. The foregoing information was compiled and provided by:
DTIC-OCA, Initials: VM_ **Preparation Date**: 1/5/99__

The foregoing information should exactly correspond to the Title, Report Number, and the Date on the accompanying report document. If there are mismatches, or other questions, contact the above OCA Representative for resolution.